Geoarchaeology An International Journal

Mining Modification of River Systems: A case study from the Australian Gold Rush

Journal:	*Geoarchaeology*
Manuscript ID	GEO-19-051.R1
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	n/a
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Mining Modification of River Systems: A case study from the Australian Gold Rush

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Abstract
Mobilisation of large volumes of bedrock, regolith and soil has long been a characteristic feature of metal mining. Prior to the 20th century this was most efficiently achieved through harnessing the motive power of water. Large-scale water use in mining produced waste sands, gravels and silts that were flushed downstream, triggering changes in stream and floodplain morphology and function. During the 19th century the shift from artisanal to industrialised mining resulted in a rapid increase in the scale and extent of environmental change. This paper presents results from a multi-disciplinary research program investigating the environmental effects of 19th-century gold mining on waterways in south-eastern Australia. Archaeological and geospatial landscape survey are combined with historical data modelling and geomorphological analysis to examine the extractive processes that produced sediment in headwater regions and how this influenced fluvial processes operating on downstream waterways and floodplains. Our case study of the Three Mile-Hodgson Creek system on the Ovens (Beechworth) goldfield in north-east Victoria indicates that miners mobilised up to 7.3 million m^3 of sediment in this small catchment alone. Results of the research suggest that tailings dams and sludge channels in this catchment are important archaeological evidence for early attempts to manage industrial waste.

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Introduction

Metal mining has been a significant driver of landscape change for millennia, as miners in search of copper, tin, gold, silver, lead and other minerals excavated shafts and voids, discharged waste onto floodplains and cleared forests for fuel (Lewin and Macklin, 1987). Until the 20th century, flowing water has provided the most efficient mechanism for removing overburden and processing ore. The waterborne waste that resulted has been redeposited on floodplains downstream from mining regions throughout the world (Clement et al., 2017; James, 1999, 2004; Lecce & Pavlowsky, 2014; Macklin, 1996; Macklin et al., 2006; Macklin & Lewin, 2018). Water use for metals processing has triggered complex downstream changes in stream dynamics, resulting in waterways re-shaped by industrial, geomorphological and hydrological processes (Macklin, 1997). Gold rushes around the Pacific Rim in the 19th century introduced large-scale metals mining to regions where it was previously unknown (May, 1980; Mountford and Tuffnell, 2018). At the same time, the mining industry drove development of technological advances that increased the scale and efficiency of water use and consequent sediment production. The impact of industrialised mining on New World waterways was rapid and transformative.

Our case study from south-eastern Australia uses the analysis of one waterway to examine the scale and complexity of change and the intersection of human and fluvial processes that continue to shape the morphology of the stream. The integration of archaeological, geospatial, historical and geomorphological approaches reveals a range of factors shaping the river and how it can be understood as an entangled cultural landscape. We argue that this approach provides a particularly useful methodology for understanding the modern shape of waterways as it makes explicit the connections between human actions and their intended and unintended geomorphological consequences. This paper presents the archaeological and historical evidence of human action that shaped the valley.

Few rivers in the world today have not been modified by human activity. Most have been artificially diverted, narrowed, shortened, channelled, dredged, dammed and otherwise changed in numerous other ways. Rivers have been modified to fit human purposes, interwoven with our projects and actions. Human behaviour is also closely linked with unintended changes to fluvial landforms associated with sedimentation (Brown et al., 2016; Lewin, 2010). A wide range of historical human activities, including land clearance, agriculture, mining and urbanisation have caused erosion and the generation of anthropogenic sediments (Macklin et al., 2014). Rivers are also increasingly recognised as active agents that shape cultural processes and act as driving forces in human events. Waterways are environmental entities but part of the cultural landscape as well, with their own biographies and histories (Cioc, 2002; Cook, 2019; Schönach, 2017). They are neither purely natural nor entirely cultural but rather entanglements of both. As such, rivers, their banks and the water flowing within them are a dynamic and vibrant kind of material culture. Archaeologist Matt Edgeworth calls them 'wild artefacts' whose flow may be managed but the wildness can never be entirely constrained (Edgeworth, 2011).

The general impact of gold mining on waterways is now well recognised in many areas including New Zealand (Clement et al., 2017; Hearn, 2013), Papua New Guinea (Bolton, 2009), Tasmania (Knighton, 1989) and the United States (Alpers et al., 2005; Isenberg, 2005; James, 1999; Lecce & Pavlowsky, 2014; Morse, 2003; Singer et al., 2013), as well as Europe

(Dennis et al., 2009; Macklin et al., 2006, 2014) and South America (Miller et al., 2004). Like other 19th-century gold rushes around the Pacific Rim, miners in Australia used large volumes of water to process auriferous washdirt through their alluvial mining claims (Carpenter, 2012; Davies et al., 2011; May, 1970). This quickly changed the hydrology of waterways by mobilising significant amounts of coarse and fine sediment. Sedimentation led to the scouring of creek beds, erosion of banks and streams and the redeposition of mining waste as tailings further downstream.

The impact of gold mining on Australian waterways was particularly severe in the colony (later, state) of Victoria where the gold rush was most intense. An earlier paper (Davies et al., 2018) described the general scale of impact of the Victorian gold rush on rivers and streams and demonstrated that three-quarters of Victoria's major river systems experienced some level of mining pollution. There are, however, no published studies that reconstruct the detailed history and impact of gold mining in a single river catchment in Australia. Thus, this paper complements Davies et al. (2018) by reconstructing the history of mining methods, cultural practices and regulation, as well as impacts on waterways in a single catchment. We investigate the Three Mile-Hodgson Creek system in north-east Victoria, a tributary of the Ovens River (Figure 1). This creek is a significant and representative example of the development and impact of alluvial gold mining that persisted for a century after 1851. Much of the land along Three Mile-Hodgson Creek has remained in public hands as river frontage and state forest, thus preserving archaeological remains from subsequent development. The integration of archaeological and geomorphological approaches adds further insight into the creation of an anthropogenic waterway over the past two centuries. This approach facilitates the recording of archaeological features in the upper catchment associated with metals extraction, the identification and characterisation of pollution-control features mid-catchment, and the interpretation of geomorphic processes that continue to shape the waterway in the lower catchment. Further, this case study illustrates the conflict that emerged between the upstream miners and downstream agriculturalists that was a hallmark of the gold-mining period (Lawrence & Davies, 2014, 2019).

Three Mile-Hodgson Creek

The Three Mile-Hodgson Creek system rises in steep, wooded terrain along the Great Dividing Range at an elevation of almost 800 m and drains an elevated plateau surrounded by higher hills. The main tributaries, Two Mile, Three Mile and Six Mile Creeks flow west through confined valleys and join to become Hodgson Creek at about 450 m before traversing an open plain and joining the Ovens River at an elevation of around 200 m. The maximum reach length is 36.7 km and the total area of the catchment is 142 km^2. The climate is mild temperate, with average maximum temperatures ranging from 27°C in summer to 11°C in winter. The average annual rainfall in the higher elevations of the catchment is 1150 mm/year, falling to 670 mm/year on the floodplain (Bureau of Meteorology). Streamflow data have not been recorded for this waterway. The primary tributaries, Two Mile, Three Mile and Six Mile Creeks were extensively mined and are now revegetated. LiDAR imagery is available for part of Three Mile Creek and shows extensive modification by alluvial mining and archaeological evidence of water races, sluicing pits, tail races and sludge dams (Davies et al., 2016a).

Miners were initially attracted to deposits of gold-bearing Tertiary and Quaternary alluvial and colluvial sands and gravels along creeks and drainage lines. Fine auriferous alluvial gravel was concentrated in narrow gullies cut into the granite and sedimentary beds. While primary gold was present in quartz reefs, secondary (placer or alluvial) gold in Pliocene and Pleistocene alluvium has historically yielded the majority of gold production (O'Shea, 1981; Phillips et al., 2003). Miners also worked other substantial water catchments draining the Beechworth plateau including Nine Mile-Yackandandah Creek and Spring-Reedy Creek. Alluvial cassiterite (tin) deposits were also mined in the area in the 19th century.

Three Mile-Hodgson Creek was exploited by gold miners for the full span of the gold rush from the 1850s until the Second World War. Miners harvested water from the upper sections of the watershed dividing the Yackandandah, Spring and Three Mile Creeks systems and diverted large volumes to their working claims (Figure 2). Mineral extraction took place along the upper and middle reaches of Two Mile, Three Mile and Six Mile Creeks. Waste was flushed into the creeks and deposited downstream, primarily on the wide floodplains around Tarrawingee. Substantial sludge control measures were eventually put in place including tailings dams on the middle reach of Three Mile Creek and channelization of the lower reach at Tarrawingee. In historical usage, 'washdirt' was auriferous gravel, sand or clay in which the greatest proportion of gold was found, while 'alluvium' referred more broadly to the gold-bearing soils, clays and gravels found in the beds, banks and adjacent terraces of creeks and gullies. 'Tailings' were the solid fraction that resulted from processing ore, while 'mullock' was the barren waste rock extracted from mine shafts and adits (Ritchie and Hooker 1998). 'Sludge' was the common term for the waste slurry of sand, clay and gravel that resulted from alluvial mining activity.

Mineral extraction

Prospectors identified payable quantities of gold on tributaries of the Ovens River in February 1852, only 15 years after British pastoralists seized the area from its Aboriginal owners. Within a year there were reported to be about 8000 diggers on the Ovens goldfield, with administration centred on the town of Beechworth (Flett, 1970; Woods, 1985). The population of the goldfield increased to 12,000 in the late 1850s but declined thereafter (Lloyd, 2006). The mining area of Three Mile Creek, now known as Baarmutha, lies about 3 km south of Beechworth. Indigenous people referred to the area as 'Barmootha', the place of several creeks (Woods, 1985). Unlike elsewhere in Victoria where nuggets were common, most gold found in the area was in the form of fine grains or flakes distributed through alluvial deposits of oxidised sands, gravels and slate. The population of the valley peaked in 1857, when 5464 people were recorded at Two, Three, and Six Mile Creeks (Census, 1857). As the easily accessible gold ran out, however, numbers dwindled to a few hundred by the early 1860s.

Initial claim sizes were only 12 feet (3.6 m) square which allowed large numbers of miners to dig in a limited area. Individuals and small parties of miners dug shallow shafts on their claims to reach the washdirt. Processing was small-scale and artisanal during this phase, with miners carting washdirt to streams where they used pans, cradles, tubs and puddling machines to separate the gold. The valley was soon pock-marked with shafts and piles of waste rock (mullock) along the creek banks and higher up the hillsides. Most archaeological evidence of this artisanal phase has subsequently been removed by later, more efficient mining methods but some sense of its likely appearance is visible in LiDAR imagery of nearby goldfields worked at this time (Figure 3).

By the mid-1850s innovations in the supply of water began to transform artisanal mining to an industrial scale of processing. This was consolidated in the 1860s when the more efficient management of water became key to exploiting the goldfield (Davies et al., 2016b). The changes were triggered by new regulations in 1853 that enabled miners to amalgamate small individual claims into larger blocks on previously worked ground that could be mined more efficiently (Birrell, 1998; Davies & Lawrence, 2014). Miners sought improved water supplies to exploit the larger claims and began excavating extensive networks of open channels (known as races) to transport water from sources higher in the catchment to their claims (Figure 4). They built dams to store seasonal creek flows and dug tunnels into hillsides to exploit groundwater supplies. These were sophisticated and high-capacity systems that transferred water along contours and between catchments. In 1868 there were over 900 km of water channels in the mining area around Beechworth (Smyth, 1980). By the mid-1880s there were at least 17 water right licences held in the Three Mile Creek catchment, in addition to numerous unrecorded water privileges retained by holders of miner's rights. Miners along Three Mile Creek were licensed to capture and divert up to 47.5 ML of water per day (Table 1). The region was a centre of innovation in Australian mining water management during this period and disputes over water ownership mediated through local courts provided the basis for much of later Australian water law (Davies & Lawrence, 2019).

Victoria's first water races for mining were built in the Beechworth region in 1853 (Lawrence et al., 2016; Davies et al., 2016b). Initially they were short channels 1-2 km in length that diverted surface water from streams into adjacent dry gullies, but they quickly grew in size and sophistication. The longest races were up to 70 km in length and the largest water companies were licensed to divert and use millions of litres each day. By 1870 one operator in Three Mile Creek, John Pund, had consolidated several earlier networks and extended his supply network over 19 km. Mining water supply around Beechworth was also unique in Australia for its exploitation of groundwater. Tunnels similar to mining adits were cut into hillsides as early as the 1860s to augment surface water supplies. Water magnates like Pund controlled multiple tunnels as part of their supply networks. The tunnels tapped springs along the divide between the Three Mile Creek (Ovens River) catchment and the Nine Mile Creek (Kiewa River) catchment, diverting significant amounts of water in interbasin transfers.

Improved water supply and the expansion of claim sizes enabled miners to use larger flows of water to loosen deposits of overburden. One technique was box or ground sluicing which originated in a Cornish tin mining technique called 'streaming' and arrived in Victoria via the California goldfields (Lawrence & Davies, 2015). The method relied on a channel of flowing water directed over a working face, with timber sluice boxes set into a tailrace lined with ripples to catch the tiny flakes of gold. Water could be stored in dams or run directly out of streams depending on available space for dams. Sluices could be very large operations. On Three Mile Creek in 1886 John Pund claimed to have 3400 m of sluice boxes (Sludge Board, 1887). Teams of men pushed washdirt into the boxes and forked out the cobbles and large gravels into stacks on site, while allowing finer sediment to wash through and into the creek downstream.

Sluicing was a gradual and systematic method that enabled large areas of ground to be efficiently processed. By the 1870s ground sluicing had been augmented with hydraulic sluicing. This technique used high-pressure water delivered by pipes, hoses and nozzles to wash away large volumes of overburden and sediment. Ground and hydraulic sluicing allowed miners to profitably work lower-grade ore deposits and effectively ended the days of artisanal mining by small parties. The new techniques depended on the amalgamation of small claims and significant capital investment in water-supply infrastructure (Davies & Lawrence, 2019). At Three Mile Creek the big sluicers quickly washed away the pillars of ore between the shafts on old claims and began to create large voids. The largest void recorded along Three Mile Creek was excavated by John Pund and his associates. It covers an area of 118 ha, with steep sides up to 15 m deep and a valley floor surface nearly devoid of topsoil. Much of the base of the void is occupied by linear mounds of gravels washed out by the sluicers and stacked on site. LiDAR confirms the void is characterised by clearly demarcated edges and a rough-textured surface, in contrast to the smoother, un-mined hills further up the slopes (Table 2; Figure 5).

Sediment mobilised by alluvial mining

We have used several approaches to estimate the amount of overburden processed by mineral extraction, as a basis for understanding sediment impacts downstream. These approaches include descriptions by contemporary observers, extrapolations from historical population data, reports on sluicing and suspended sediment from the Sludge Abatement Board in the early 20th century, and LiDAR survey.

Mining surveyor Henry Grimes mapped Three Mile Creek in 1861, providing the earliest reliable source of information on sediment production (Grimes, 1861). Grimes visited the workings and mapped the depth of washdirt then visible. He recorded depths at 13 locations in the Three Mile workings and nine locations in the Two Mile workings nearby. Auriferous clays, gravels and sands in Grimes' survey ranged from 1 m to 6 m in depth. Miners typically sluiced 4 m or more of this deposit (Sludge Board, 1887). Allowing for an average depth of 4 m of deposit removed by sluicing, the primary mining scar on Three Mile Creek is estimated to have been the source of approximately 4.7 million m^3 of alluvium.

A complementary approach is to estimate the sediment produced by each party of sluice miners using population data recorded in mining surveyors' reports, census and other historical sources. Available data cover the periods 1857-1861, 1864-1867 and 1869-1889, providing a coverage of 30 years or more than half of the 19th-century mining period. The period 1857–1860 saw 3-4000 miners in the valley but this soon declined so that there were generally around 300 miners working in the Two, Three, and Six Mile Creek area during the 1860s and 1870s. The population declined further to around 200 during the 1880s. We extrapolate this lower 1880s average to the 1890s, when a similar scale of mining activity occurred (Secretary for Mines, 1891-1901). Around 80 reef mines were also worked in the catchment, where auriferous quartz was excavated at depth and hauled to the surface for crushing in a stamp battery. These operations, however,e were mostly short-lived and employed only small numbers of workers (DPI, 2002; Lloyd, 2006). We assume sluicing parties generally worked in small groups of three (Smyth, 1980). Volumes of washdirt were historically measured in cubic yards. We use a conservative scale factor of 5 cubic yards (3.825 m^3) per day of overburden and washdirt mobilised per sluicing party, working for 200 days of the year. On this basis each sluicing party could shift approximately 1000 cubic yards (765 m^3) per year. This is a conservative estimate and in many cases miners mobilised much larger volumes of alluvium (Smyth, 1980). Despite several gaps in the data, this method indicates that miners in the Three Mile area mobilised approximately 6.1 million m^3 of earth material for the period 1851-1900 (Table 3).

Pund & Co was the major sluicing party on Three Mile Creek during the 20th century. Companies were obliged to report the quantity of alluvium treated but this was often neglected. For the period 1903-1918 Pund reported a total of c.440,000 m^3 of alluvium (Secretary for Mines, 1903-1918). Pund's leases were purchased by G.S.G. Amalgamated in 1919, after which this group was the only major sluicer on Three Mile Creek, operating until 1947. During this period the company worked an estimated 765,669 m^3 of material (Department of Mines, 1919-1947). Historical sources thus indicate that the total volume of sediment mobilised by sluicing activity in the valley of Three Mile Creek included 6.1 million m^3 (19th century) + 1.2 million m^3 (20th century) for a total of approximately 7.27 million m^3.

A third source of information derives from reports by the Sludge Abatement Board, which was formed in 1905. In 1911 the Board reported that, from the beginning of the gold rush at Beechworth in 1852, more than 15 million cubic yards (11.5 million m^3) of 'overburden and wash' had been sluiced away from the hills, creek beds and terraces of Reedy Creek and Hodgson Creek (SAB, 1912). Reedy Creek drains the northern sluicing area of Beechworth and represents roughly half of this total. On this basis the Board's estimate of 5.7 million m^3 of sediment discharged down Hodgson's Creek from 1852-1910 is broadly consistent with our calculations, allowing for additional mining from 1910 to the 1940s.

Our final method of calculating the volume of sediment removed by mining has been using GIS analysis to drape a reconstructed surface across the scar recorded by LiDAR in Three Mile Creek (Figure 5). This provides an estimate of the void of approximately 4.2 million m^3. Additional, smaller volumes of sediment were mobilised by miners in the Two Mile and Six Mile Creek tributaries, thus adding to the volume discharged down the valley (Rutherfurd et al. forthcoming).

Estimates from the three latter sources are broadly consistent. The Board's estimate of 5.7 million m^3 of sediment discharged down Hodgson Creek from 1852-1910 is higher than our estimate from LiDAR that only considers mining in Pund's leases, and slightly lower than our estimate from Mines Department reports that extends the data by several decades to the 1940s. From these figures it is evident that miners mobilised significant volumes of sediment. This demonstrates the same trend in anthropogenic overburden production recently described by Cooper et al. (2018) but places it several decades earlier than their analysis begins. In an era before the widespread use of the internal combustion engine, the effective harnessing of water as a motive force was central to earth-moving at this scale. Using water to sluice for gold transformed large volumes of the earth into liquid waste.

Mine waste and pollution control

Sediment mobilised by mining and sent downstream as sludge did not go unchallenged. Widespread protests against mining waste around Victoria, led in part by the community of the Ovens Valley, were ultimately responsible for the introduction of the *Mines Act* 1904, Australia's first legislation to control mining pollution(Lawrence & Davies, 2014, 2019). This legislation aimed to stop pollution at its source by making miners responsible for the waste they produced. In Three Mile-Hodgson Creek this meant construction of settling dams in the middle reaches of the catchment. Tailings dams were used to trap and store waste material discharged from mining operations and are the precursors of the tailings dams used in industrial mining operations today (Hudson-Edwards, 2016). The 1850s gold rush was the first industry in Australia to generate substantial volumes of industrial waste (Royal Commission, 1859). While legislation and regulation were the social mechanisms of control, the dams themselves provided the means to manage pollution on the ground. The archaeological evidence of tailings dams along Three Mile-Hodgson Creek are thus significant sites of early industrial waste management in Australia.

Bye-laws gazetted from the late 1850s directed miners to build dams for retaining sludge but the degree of compliance and enforcement in these early years was not high. Sludge dams became more common by the 1870s when several came into use along Three Mile Creek. Some miners expediently turned to old water storages to meet their obligations. In 1878, for example, John Pund acquired a large reservoir from Chinese miner Ah Gee and used it for water storage until it filled with 'slum' or sludge and then built another reservoir upstream. Others constructed purpose-built sludge dams such as that built by Friedrich Kassebaum at Upper Three Mile Creek c. 1881 (Figure 6; Table 4). Neighbours of Pund and Kassebaum on Three Mile Creek were also building sludge dams by the 1880s including William Varley, Philip Busch and James Gillies (Sludge Board, 1887:3-10). Sludge dams became much more common in the twentieth century because of the new anti-pollution regulations which were enforced by the independent Sludge Abatement Board. In 1911 John Pund built a series of sludge dams in the lower part of Three Mile Creek after being prosecuted by the SAB (SAB, 1912). Using multiple dams meant that one dam could be filling while the embankment of another was being raised. The area of Pund's settling basins covered about 1.8 ha, with embankment walls up to 4 m in height and 400 m long (SAB, 1913).

From the early twentieth century the Sludge Abatement Board published detailed instructions for miners on how to build sludge dams (e.g. SAB, 1907). Construction generally involved building up an embankment (sometimes referred to as a 'breast') of alternating layers of earth and brushwood (Figure 7). Log piles, clay, sludge and tailings could also be used, depending on local conditions. Lightweight materials allowed water to percolate through the dam wall while retaining coarser sediment. The height of dam walls increased gradually to accommodate successive inflows of sludge. Stone masonry dams were built occasionally but these were expensive and generally unpopular. The dams varied in size depending on the nature and scale of the claim they served. The walls of sludge dams typically extended up to several hundred metres in length and ranged from 1 m to 5 m in height (Table 4).

The archaeological remains of eight sludge dams have been identified in the catchment of Three Mile Creek. Most were constructed during the first half of the 20th century. Embankments range from 0.5 m to 5 m in vertical height and two examples are more than 300 m long. Sludge dams have several distinctive characteristics, revealed in LiDAR imagery and the archaeological remains. Each dam shows up as a large flat feature with little or no surface relief and bound by a straight embankment on the downstream edge (Figure 8). The appearance of the dams contrasts sharply with adjacent areas, whether heavily disturbed and pockmarked mining areas or naturally contoured hillslopes. In aerial photography from the 1940s dams in use during the 20th century show up as bright white surfaces, while older dams have become overgrown with vegetation and are no longer easily visible (Figure 9).

Field survey indicates that in most circumstances the dam walls themselves have disappeared as they were built of organic materials that have subsequently decomposed. What remains is the actual sludge, consisting of laminated deposits of fine-grained, size-sorted silts that have filled the retaining ponds built to hold them. Where the dam wall was built across valleys the deposit shadows the shape of the original reservoir, with a long, straight and steeply sloping edge on the downstream face and lensing out against the hillslopes on the margins. Kassebaum's dam on Upper Three Mile Creek takes this form with an eroding face that is up to 5 m in height and extends for nearly 100 m. In other instances, the shape of the surviving mound suggests that timber retaining walls were built on the sides as well as the leading face of the area enclosed. This was the case at Pund's lowest dam on the right bank of Three Mile Creek at Voigts Road (Figure 10). The sludge appears now as an extensive flat-topped mound of earth 5.2 m high and 1.8 ha in area. The eroding faces of the mound indicate that the dam wall was built part-way across a wide valley with a retaining wall parallel to the creek. Thus the dam had the effect of substantially narrowing the valley floor.

Modern vegetation on the surface of sludge dams differs from plant cover in immediately adjacent areas. Vegetation on the surface of sludge dams in Three Mile Creek is dominated by exotic grasses and gorse, along with native grasses (*Poa sieberiana*) and rushes (*Juncus amabilis*). The density of eucalypts (Red Box and Yellow Box) is much lower on sludge dams than on neighbouring creek banks (Figure 10). Sludge dams are also very poor in native herbs and have little or no shrub layer. Vegetation is thus heavily disturbed, with a low diversity of exotics and natives and sparse canopy formed by larger trees. Grazing of vegetation on the sludge dams and in the mining voids is generally limited to native fauna (kangaroos, wombats, etc).

The aggregate volume of sludge retained in these dams is approximately 179,000 m^3 (Table 4). This represents, however, only a small proportion (2.5%) of the total volume of sediment (7.3 million m^3) mobilised in the valley by alluvial mining. Sludge dams thus played only a limited role in reducing sludge flows downstream. Moreover, miners often took advantage of high creek flows to flush out their sludge dams to make space for more tailings, probably by directing the streams through the dams. Laurence Murphy explained to the 1887 Sludge Inquiry that miners had cleared out dams in this way 'for the last 28 or 30 years' (Sludge Board 1887:15).

The reuse and recycling of dams and reservoirs has several implications for the archaeological identification of sludge dams. It means that sludge dams identified on the ground may originally have been constructed as reservoirs for water, and thus may also need to be considered as part of water supply infrastructure. It also raises the possibility that earlier sludge dams may have been removed by later mining activity that reworked them for their residual gold content.

Floodplain change

Sediment mobilised by mining that escaped the sludge dams was carried downstream to the floodplain reach of the system. Here the waterway underwent rapid anthropogenic change, with sediment filling the creek channel and spilling out onto the floodplain . Early European accounts before the mining period describe Hodgson Creek as 'a pure and limpid stream', traversing open woodland country with numerous billabongs or lagoons (Dunn, 1871). This indicates the anabranching network of shady streams connecting deep pools and wetlands that was used by the Yorta Yorta, Taungurung, Dhudhuroa and Yaitmaithang peoples for thousands of years (Humphries, 2007). Upstream mining activity transformed the floodplain within only a few decades and today this section of Hodgson Creek is characterised by features that are the consequence of minerals extraction. The first feature is a distinctive layer of sediment capping the stratigraphic profile along both sides of the creek for most of its length across the floodplain. The second feature is the morphology of Hodgson Creek itself, which is now a straightened and deeply incised channel. Understanding the connection between mining activity in the upper reaches and fluvial processes on the plains means these characteristic features can be better understood.

Three Mile Creek flows from its confined valley and emerges as Hodgson Creek on the floodplain of the Ovens River. Where the bank of the creek has been exposed through erosion there is a clearly visible band of pale yellow (10YR 5/6) sediment at the top of the soil profile. This distinctive band is generally 1-2 m thick and has been identified along the banks of the creek for most of its length across the floodplain (Figure 11). The yellow band sits above a dark grey (10YR 4/1) organic floodplain deposit. Macroscopic examination of the mining sediment band reveals that it is comprised of multiple thin laminations of fine-grained silt interspersed with occasional sandy lenses. This sediment has substantially changed the soil structure of the floodplain. The previous structured profile rich in organic matter has been buried by a uniform deposit that is largely devoid of organic material. Similar mining-related deposits have been described in rivers in New Zealand (Clement et al., 2017), the UK (Howard & Macklin, 1999; Macklin et al., 2014) and California (James, 1999).

The recent origins of this sediment layer are documented in archival records of complaints from residents beginning in the 1860s. The timing and extent of landscape change are the result of industrialisation intersecting with local hydrology. The district featured some of the finest agricultural land in the region and British settlers eagerly established farms around the township of Tarrawingee from the mid-1850s (Woods 1985). Although mining was already well underway in higher country to the east, complaints did not begin appearing until the late 1860s (e.g. *OMA*, 5 August 1869:2f). It was at this time that the move from artisanal to industrial water use in the upper catchment began to generate much larger quantities of polluted slurry or sludge. A series of major floods also contributed to the downstream transport of sediment. Annual floods became the norm as the channel of the creek filled with sludge but it was after major floods in 1867, 1870, 1880, 1887 and 1896 that complaints escalated.

Following the 1867 and 1870 floods, residents reported that the whole country had an 'appearance of desolation and destruction' and estimated that 4000 hectares of good land had been inundated with sediment (*Argus*, 7 September 1875:5b; *OMA*, 22 June 1878:8a). One farmer described how 'the creek silted up till it got quite level with the banks, there was no creek at all, it flowed over every place year by year… I have seen it at times three miles wide, only a sheet of yellow water, slime and mullock, from the mines' (Sludge Board 1887:145). By 1886 two metres of sludge had filled the creek and was covering the tops of fences (Sludge Inquiry 1887:148). In one location 'three fences have had to be erected one above another' (*OMA*, 14 November 1903). The sediment itself is described as 'yellow, slimy clay', 'sand and slate', and 'red soil [that] lies like cement over the land, and months elapse before the ground recovers itself (Sludge Board, 1887:143, 145; *OMA*, 14 November 1903:8g).

These descriptions of the extent and character of the sludge are consistent with the observed floodplain stratigraphy. They demonstrate that paleosols associated with the boundary between the yellowish silts and sands in the upper sediment unit and the dark sediment in the lower unit would have been on the surface in the 1850s. Identification of the recent anthropogenic origins of the upper stratigraphic unit has implications for the preservation and recognition of Aboriginal cultural heritage. Survey and excavation strategies associated with cultural heritage management activities along waterways downstream from goldfields areas must be designed in the expectation that Aboriginal artefacts (e.g. worked stone, hearths, mounds) will be preserved at some depth below the present ground surface even when surface evidence is absent.

Sludge Channel

The floodplain reach of Hodgson Creek is no longer anabranching and is now a single straightened channel, having developed within a steeply eroded trench approximately 6 m deep and up to 25 m in width. Erosion of the stream has facilitated identification of the floodplain sediment layer now visible in the exposed section. Confinement of the waterway in a single channel, lack of sinuosity and incised morphology are all consequences of the historical community action taken to limit the sludge damage and the fluvial processes of readjustment that followed. The intersection of human and fluvial action has established the creek's form as a highly manipulated cultural artefact.

Channelizing and straightening of Hodgson Creek occurred during the 1880s, removing the stream meanders and creating a straight channel with a steeper gradient (Figure 12). The Victorian government began spending large sums on drains to alleviate the sludge problem at various mining centres from the late 1850s but the Ovens goldfield was overlooked for many years, despite decades of complaints and protests from local farmers (Lawrence & Davies, 2014). Construction of the Tarrawingee sludge channel finally began in April 1879, with most of the work done over the following decade with shovels and wheelbarrows (Kay, 1954; *OMA*, 19 April 1879:8a). The two local government authorities responsible, however, each built their section of the channel to different engineering specifications. The North

Ovens (downstream) section was, to begin with, 0.9 m wide at the base, with sloping banks and embankments on each side giving a depth of 3.2 m and a maximum width of 10 m (*The Age*, 19 April 1879:5g). This section of the channel had a fall of 3.8 m per kilometre (Sludge Board 1887:147). The Beechworth (upstream) portion, however, was designed to carry a much larger volume of mining waste and flood water (*OMA*, 10 April 1884:2b, 10 December 1885:1d).

By 1885 there was still a gap of almost 750 m between the two sections of the channel and sludge remained a major problem (*OMA*, 14 March 1885:8e). In 1886, with the channel still not completed, the Sludge Inquiry Board heard evidence from 18 local farmers who were almost unanimous in condemning the sludge that flowed across the floodplain (Sludge Board, 1887:143-159). The following year, 1887, was characterised by the worst flooding in decades, with damage to farmland, roads, bridges and the banks of the sludge channel itself (*OMA*, 12 November 1887:2a). The gap in the unfinished channel persisted for years but the enterprise appears to have been completed by 1890, with the lower section extending 4.4 km from the Ovens River to the north-east and then turning sharply east for 3.8 km to merge with the lower part of Hodgson Creek where it left the foothills (*OMA*, 10 May 1890:11b; Figure 13).

The channel filled almost immediately as sludge continued to flow down Three Mile Creek and in the following years the channel continued to need regular and expensive maintenance. By the end of the century, however, mining was in decline. This brought the new problem of erosion which further changed the creek's form. The first direct mention of the channel eroding comes from witnesses at a Sludge Abatement Board inquiry in Wangaratta in 1906, which indicates that sediment supply to the stream was decreasing even before the settling dams were constructed. One reported 'The channel had scoured four feet deeper since it was cut 10 years ago' (*OMA*, 16 June 1906:6). The Shire Engineer for Oxley reported that 'the sludge channel had been cleaned out 3 ft. deeper on the left and 2 ft. deeper on the right. Between the times of my visit the width was about from 8 to 12 ft. Paid a third visit and found that 3 ft. of silt had been taken off the south bank and carried down the Ovens River' (*OMA*, 16 June 1906:6).

In 1916 the SAB reported considerable erosion along the Tarrawingee sludge channel due to bad winters. In the major floods of 1917, the sludge channel eroded dramatically. Newspaper reports note that bridges all along the sludge channel were damaged by erosion and it was observed that it now operated more as a flood channel than a sludge channel. In 1920 a public meeting was called to consider the serious siltation where the sludge channel joined the Ovens River, including the formation of a complete bar across the river (*The Age*, 21 March 1918:9). It was claimed that the Ovens was up to 8 m deep above the junction with the sludge channel but completely filled with sediment downstream for several kilometres. The SAB believed that this sediment came from channel erosion rather than from mining. This appears to be the most substantial deposition reported in the Ovens River itself in the historical record.

Councilor Gunn, whose land fronted the channel, suggested that the cause of deposition in the Ovens was the construction of settling dams that sent down clear water which had begun to cut into accumulated silt in the channel and move it into the Ovens river. Eight hectares of Gunn's land fronting the sludge channel was swept away by erosion after heavy rains, and the bed of the creek was now 1.2 m lower (*OMA*, 12 June 1918:4). Alluvial mining ceased in the upper reaches of Three Mile-Hodgson Creek by the 1940s. Incision at Tarrawingee, however, was still active in the decades that followed, with continued widening and deepening of the channel by erosion threatening road bridges and other infrastructure. Landowners used the creek flats as pasture, with cattle generally having unimpeded access to the creek for water, which exacerbated bank erosion. Grade control measures, in the form of low weirs of rock and concrete, were installed in the creek during the 1990s. These helped to halt further major channel incision and downstream sediment transport, but channel widening has continued in response to unrestricted stock access and storm event-related bank erosion (Alluvium 2014, Figure 14).

Channelization of Hodgson Creek was a deliberate human response intended to manage the problems caused by mining waste, but it has had a range of adverse and ongoing environmental consequences. These include incision of the channel, reduced flows to floodplains and wetlands, and changes to riverside vegetation. The steep banks are highly erodible and the new channel precludes the formation of meanders or billabongs. Channelization reduces geomorphic diversity while increasing channel slope and hydraulic efficiency, conveying water more quickly through the channelised section. Removal of vegetation and snags reduces the resistance of channels to erosion. Channelization also results in the decline of river substrates and the deterioration of in-channel pools. Shortening the stream length and streambank complexity substantially reduces the availability and diversity of native habitat. All of these remain issues along Hodgson Creek, part of the ongoing cost of historical metal extraction.

Conclusion

The transformation of Three Mile-Hodgson Creek was part of a global historical pattern of harnessing water power on an industrial scale, with a resulting cascade of environmental effects on river channels and floodplains (Clement et al. 2017; Dennis et al. 2009; Macklin et al. 2006). Walter and Merritts' (2008) analysis of mid-Atlantic streams in the eastern United States, for example, identified thousands of millponds constructed in the 17th-19th century that inundated the pre-settlement wetlands and quickly altered regional stream functions. Sedimentation turned the millponds into sediment-filled reservoirs, with subsequent dam breaching and channel incision through post-settlement alluvium creating new landscapes of abandoned valley-flat terraces and lower inset floodplains. Their analysis demonstrated that the morphology and function of most waterways in the region are the result of recent historical and geomorphological processes, with important implications for the management and restoration of streams and floodplains.

The introduction of industrialised metal mining to Australia in the 19th century also had rapid and extensive consequences for waterways. Miners applied sophisticated water management technologies to divert large quantities of water for processing ores and used the motive power of water to move large quantities of sediment. In the process they created large and permanent voids and new stratigraphic layers as mobilised sediment was redeposited on floodplains. Attempts to retain mining sediment in sludge dams created large new terraces along valley floors. Social responses to downstream damage triggered ongoing change as human interventions continue to interact with fluvial processes. Legal innovations in pollution control legislation appeared to be effective for improving water quality but these were too limited and too late to have a significant impact on keeping sediment out of lower reaches of the stream. Sludge dams retained only a small proportion of the sediment load. It was only the decline of the mining industry that reduced the sediment supply coming from the upper catchment. Of far more lasting importance was the transformation of the lower reach of the stream into a sludge drain. Channelization that straightened the creek and increased the efficiency of water flow triggered incision and erosion as the creek readjusted to new sediment loads. The Three Mile-Hodgson Creek case study thus demonstrates that landscape modification on an industrial scale was a characteristic feature of European expansion that began well before the 20th century and the effects of that modification are ongoing. The creek system represents a rich archaeological landscape that reveals evidence of past human-river-sediment interactions which have effectively terraformed the environment both as a place of industry (upstream) and accumulated sediment (downstream).

Acknowledgements

This research was funded by the Australian Research Council (grant number DP160100799). We are grateful to Jan and Peter Nolan of Tarrawingee for their hospitality and to Jo Slijkerman for her support. LiDAR imagery was made available by a Data Access Licence Agreement between the Department of Environment and Primary Industry, the University of Melbourne and La Trobe University.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Figure captions

Figure 1: Location map showing Three Mile-Hodgson Creek in relation to the Ovens floodplain

Figure 2a: Schematic plan showing water diversion, mineral extraction and pollution control in mining area; 2b: schematic profile of sludge dam with brush layers and laminations; 2c: schematic plan showing (top) pre-mining floodplain with anabranching channels, (centre) sludge filling channels and covering floodplain, and (bottom) post-mining incision of channel through sludge.

Figure 3: LiDAR image of potholes at Reedy Creek cut by later sluicing, 10 km north of Baarmutha

Figure 4: John Pund's race network transferred water from Nine Mile Creek to Three Mile Creek

Figure 5: LiDAR image of Three Mile Creek with primary alluvial sluicing scar outlined. Colours indicate relative change in depth from the original surface, with red shading showing greatest depth below surface (source: Victorian Department of Environment and Primary Industry)

Figure 6: Sludge dam of Friedrich Kassebaum on Three Mile Creek c.1881 (source: VPRS 6784)

Figure 7: Example of sludge dam construction recommended by the Sludge Abatement Board, with green branches alternating with layers of earth or gravel (source: Sludge Abatement Board 1907:82)

Figure 8: LiDAR of Three Mile Creek showing position of four identified sludge dams (source: DEPI 2010)

Figure 9: Aerial photo of Three Mile Creek from 1940s showing sludge dams; dams 1-4 correspond with LiDAR image in Figure 8 (source: DELWP 2017)

Figure 10: Sludge dam of Pund & Co in Three Mile Creek with embankment centre-left and flat surface on the right

Figure 11: Vertical exposure of current sludge channel in Hodgson Creek at Tarrawingee showing yellow mining sludge above grey pre-European alluvium. Scale in 20 cm increments

Figure 12: Hodgson Creek cross-section comparison, located between Diffey Lane and Rusholme Road at Tarrawingee

Figure 13: LiDAR of Tarrawingee Sludge Channel (source: Victorian Department of Environment and Primary Industry)

Figure 14: Looking west down the Tarrawingee Sludge channel on Hodgson Creek showing active modern erosion. The cow in the distance provides a scale.

Table captions

Table 1: Water right licences (WRL) held on Three Mile Creek in 1884 with daily volume entitlements in megalitres (ML) (source: Secretary for Mines 1885:54-55)

Table 2: Archaeological landform features relating to alluvial mining

Table 3: Average population data by decade aggregated from Two, Three and Six Mile Creeks and volumes of sediment produced by alluvial mining, rounded to nearest thousand (sources: Mining Surveyors' Reports, 1859, 1864–1888, March quarter; Victorian Census, 1857 and 1861; Hilderbrand, 2012; Lloyd, 2006)

Table 4: Details of sludge dams on Three Mile Creek, area and volumes rounded to nearest thousand (see Figure 10 for locations)

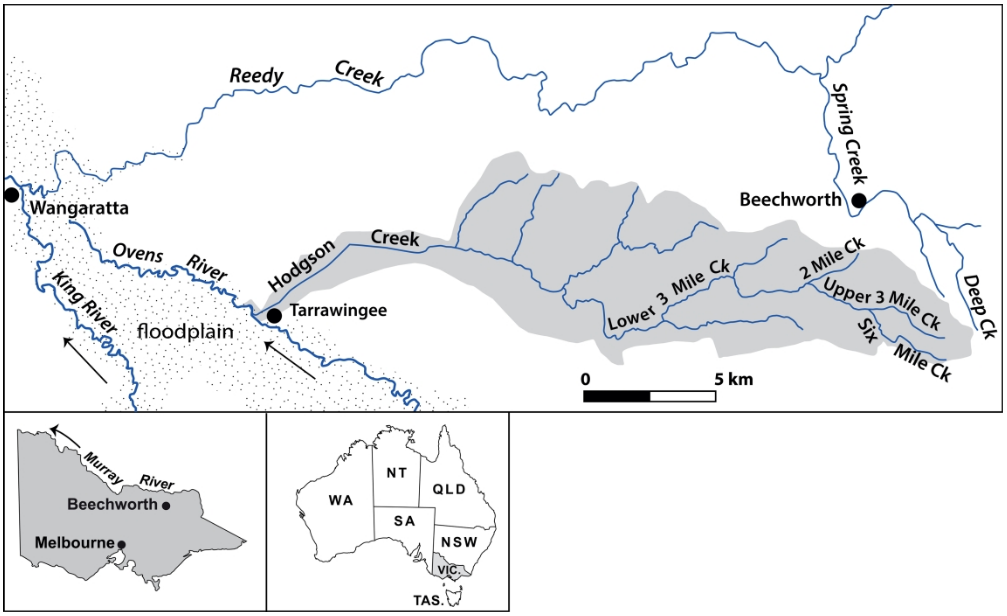

Figure 1: Location map showing Three Mile-Hodgson Creek in relation to the Ovens floodplain

149x91mm (600 x 600 DPI)

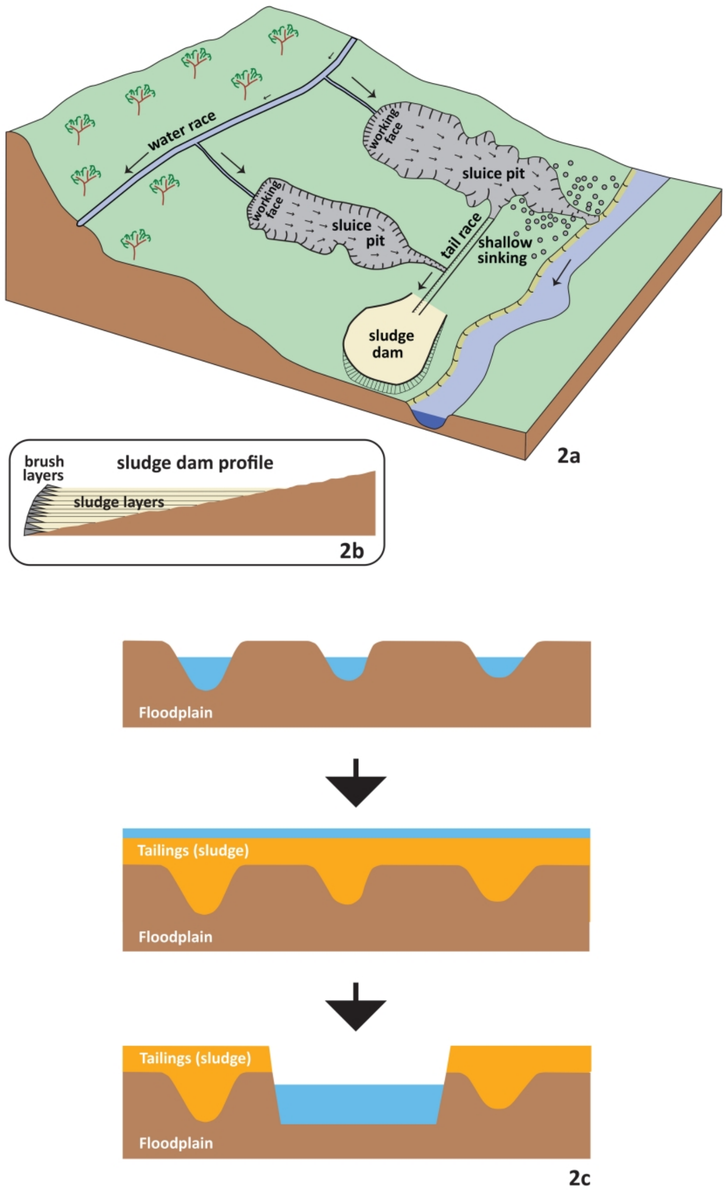

Figure 2a: Schematic plan showing water diversion, mineral extraction and pollution control in mining area; 2b: schematic profile of sludge dam with brush layers and laminations; 2c: schematic plan showing (top) pre-mining floodplain with anabranching channels, (centre) sludge filling channels and covering floodplain, and (bottom) post-mining incision of channel through sludge.

91x149mm (600 x 600 DPI)

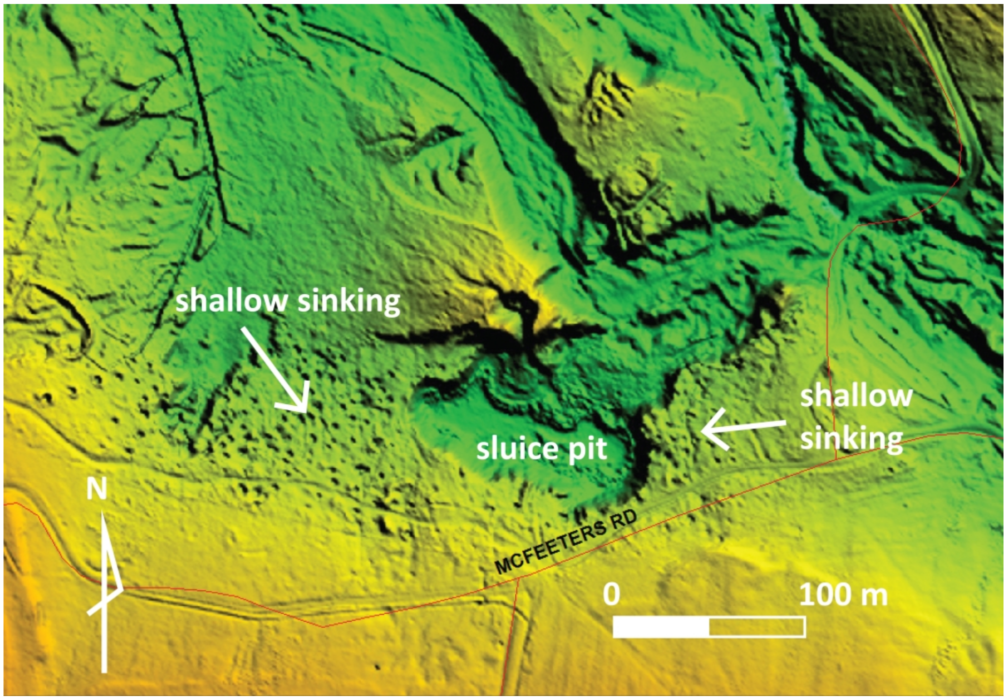

Figure 3: LiDAR image of potholes at Reedy Creek cut by later sluicing, 10 km north of Baarmutha

128x89mm (600 x 600 DPI)

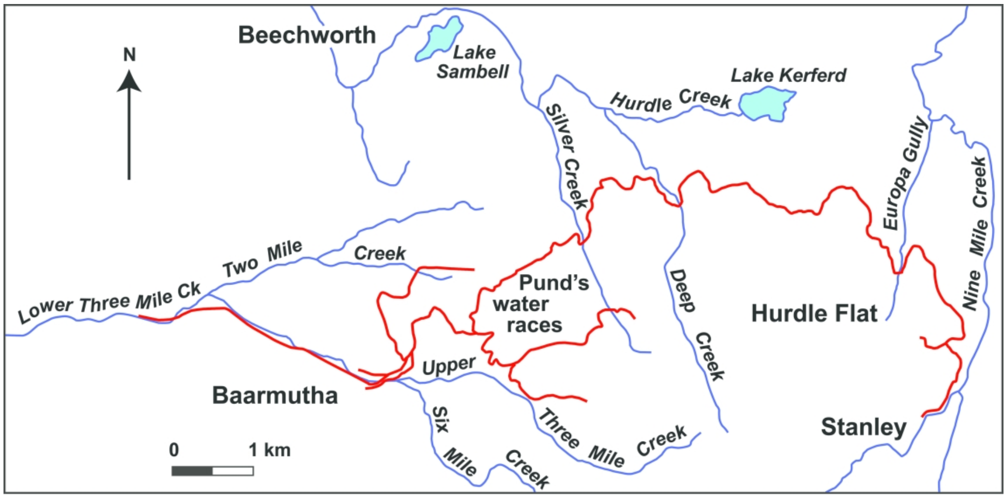

Figure 4: John Pund's race network transferred water from Nine Mile Creek to Three Mile Creek

130x64mm (600 x 600 DPI)

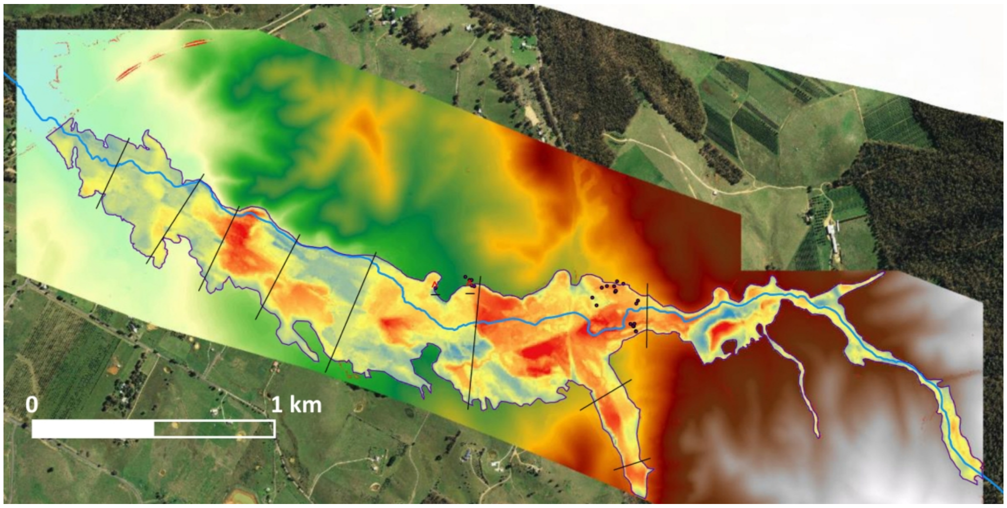

Figure 5: LiDAR image of Three Mile Creek with primary alluvial sluicing scar outlined. Colours indicate relative change in depth from the original surface, with red shading showing greatest depth below surface (source: Victorian Department of Environment and Primary Industry)

151x75mm (600 x 600 DPI)

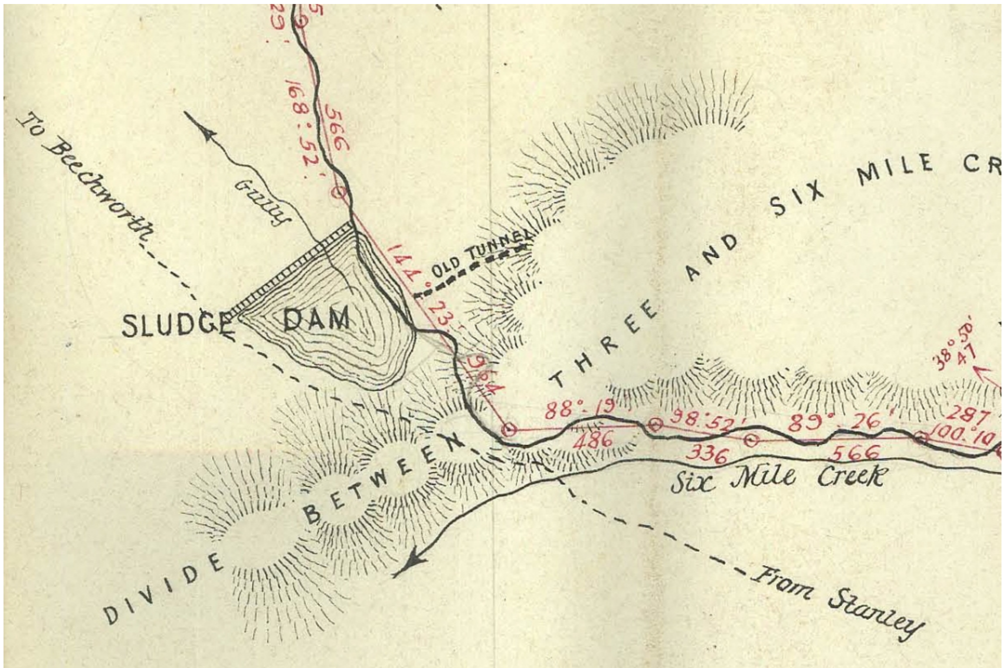

Figure 6: Sludge dam of Friedrich Kassebaum on Three Mile Creek c.1881 (source: VPRS 6784)

103x69mm (300 x 300 DPI)

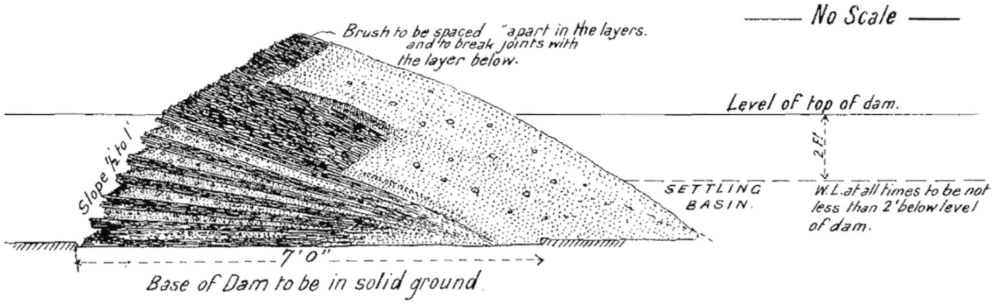

Figure 7: Example of sludge dam construction recommended by the Sludge Abatement Board, with green branches alternating with layers of earth or gravel (source: SAB 1907)

150x50mm (300 x 300 DPI)

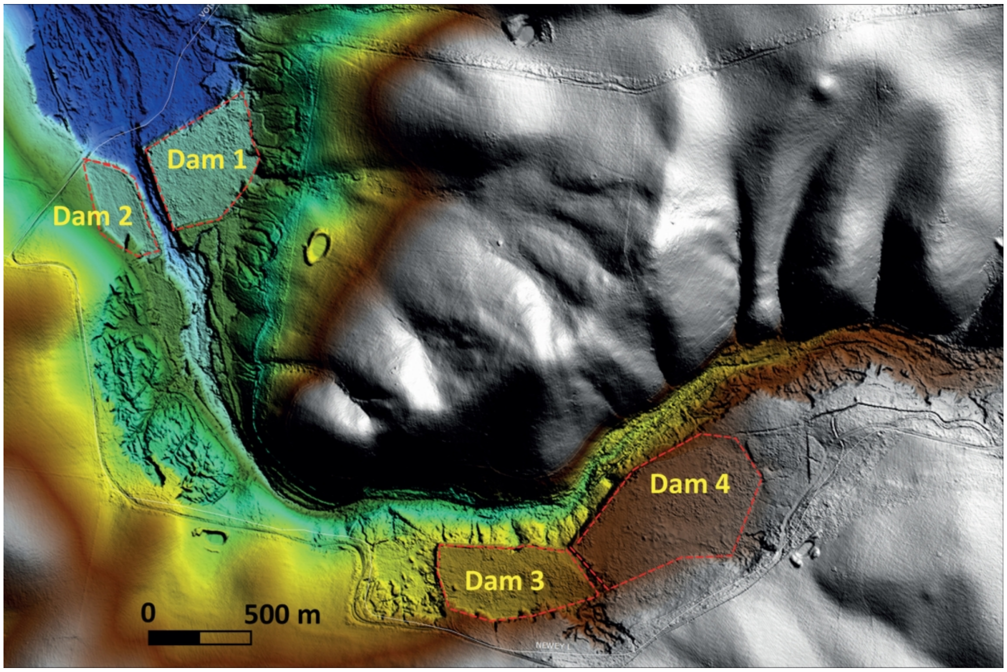

Figure 8: LiDAR of Three Mile Creek showing position of four identified sludge dams (source: DEPI 2010)

130x86mm (300 x 300 DPI)

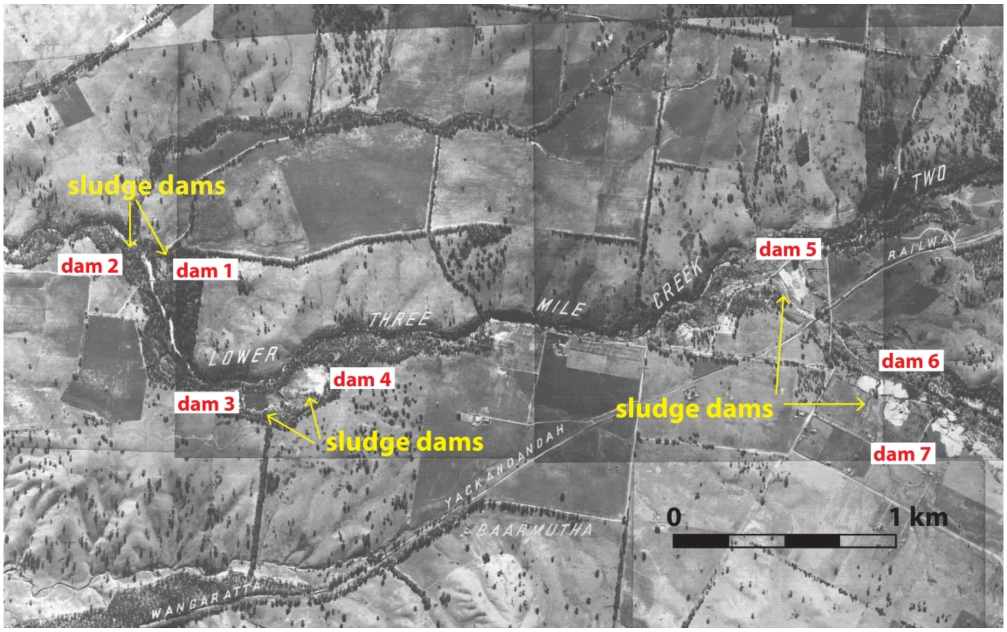

Figure 9: Aerial photo of Three Mile Creek from 1940s showing sludge dams; dams 1-4 correspond with LiDAR image in Figure 8 (source: DELWP 2017)

199x124mm (300 x 300 DPI)

Figure 10: Sludge dam of Pund & Co in Three Mile Creek with embankment centre-left and flat surface on the right

150x99mm (300 x 300 DPI)

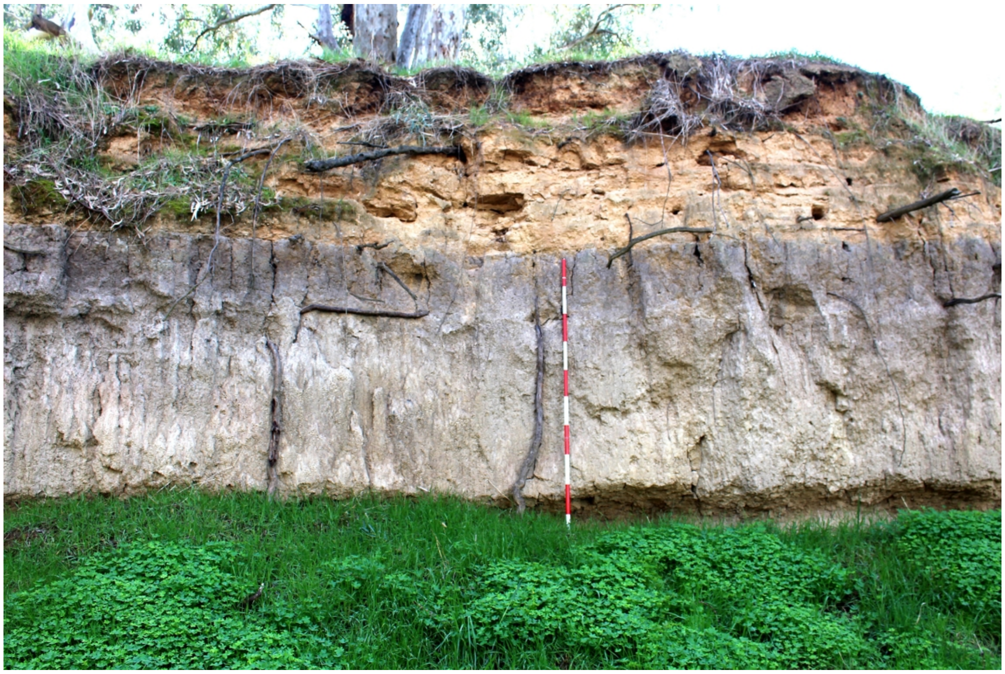

Figure 11: Vertical exposure of current sludge channel in Hodgson Creek at Tarrawingee showing yellow mining sludge above grey pre-European alluvium. Scale in 20 cm increments

199x133mm (300 x 300 DPI)

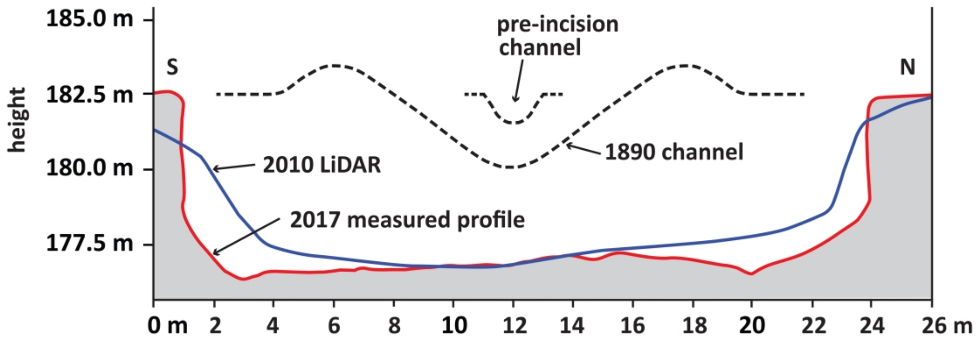

Figure 12: Hodgson Creek cross-section comparison, located between Diffey Lane and Rusholme Road at Tarrawingee

167x59mm (600 x 600 DPI)

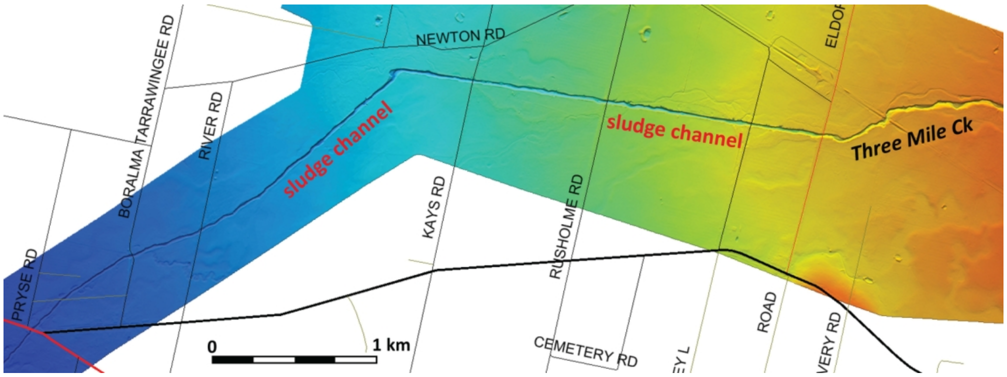

Figure 13: LiDAR of Tarrawingee Sludge Channel (source: Victorian Department of Environment and Primary Industry)

149x55mm (300 x 300 DPI)

Figure 14: Looking west down the Tarrawingee Sludge channel on Hodgson Creek showing active modern erosion. The cow in the distance provides a scale.

150x99mm (300 x 300 DPI)

Table 1: Water right licences (WRL) held on Three Mile Creek in 1884 with daily volume entitlements in megalitres (ML) (source: Secretary for Mines, 1885)

WRL No.	Date of issue	Licensee	Locality	Volume (ML)
355	15 May 1873	C Miehe & another	Upper Three Mile Creek	2.45
359	30 June 1873	M Greely & others	Three Mile Creek	1.36
360	3 Dec 1874	H Probst	Upper Three Mile Creek	1.82
442	19 Aug 1881	J Pund	Nine Mile Creek to Three Mile	4.32
451	31 Jan 1882	T Welsh	Upper Three Mile Creek	6.82
452	14 April 1882	F Kassebaum & others	Head of Six Mile Creek	2.45
455	30 May 1882	W M Hyndman	Head of Three Mile Creek	4.55
474	16 July 1883	W Telford & others	Two Mile Creek	4.55
475	30 Nov 1883	C Miehe & another	Three Mile Creek	3.64
479	12 June 1883	W M Hyndman	Three Mile Creek	0.82
480	19 June 1883	W M Hyndman	Three Mile Creek	1.27
482	12 June 1883	J Gillies & others	Three Mile Creek	0.39
483	19 June 1883	J D Law	Three Mile Creek	1.64
488	23 July 1883	W Orchard & others	Two Mile Creek	0.91
489	16 July 1883	J D Law & others	Three Mile Creek	2.27
491	5 June 1883	R Williams	Three Mile Creek	3.64
494	16 July 1883	F Kassebaum & others	Three Mile Creek	4.55
522	15 Dec 1884	W M Hyndman	Three Mile Creek, tail race	-
			Total	**47.45 ML**

Table 2: Alluvial mining landforms

Dredge pond	large hollow remaining (usually water-filled) after bucket dredging or hydraulic pump sluicing
Potholes	small pits and hummocks from the earliest phase of gold mining, where miners dug into gold-bearing gravels in stream beds and creek banks; often obliterated by later mining activity
Puddler	ring-shaped trough in the ground for puddling gold from auriferous clay, typically about 5 m in diameter
Mining dam	earthen embankment built across watercourse to impound water in a storage reservoir, 1 m to 5 m high; volume from 0.5 ML to 20 ML; sometimes re-used as sludge dam
Sludge channel	channel cut to remove sludge from mining areas and prevent inundation; creeks often straightened and realigned for the purpose
Sludge dam	embankment to trap tailings from alluvial mining, 1 m to 5 m high, usually adjacent to waterways; flat surface and sloping embankment on downstream edge
Sludge deposit	layer of mining sludge in waterway and floodplain, often 1 m or more deep
Sluice scar	steep eroded face in valley resulting from ground or hydraulic sluicing, 1 to 10 m high
Tail race	channel for rapidly conveying waste water and tailings (sludge) away from a mining site; usually with steeper pitch than water races
Tailings	solid waste from alluvial mining or ore processing; finer material generally discharged into waterways as sludge, with cobbles remaining on site or adjacent
Water race	channel or aqueduct (leat) for conveying water from creek or reservoir to mining site

Table 3: Average population data by decade aggregated from Two, Three and Six Mile Creeks and volumes of sediment produced by alluvial mining, rounded to nearest thousand (sources: Mining Surveyors' Reports, 1859, 1864–1888, March quarter; Victorian Census, 1857 and 1861; Hilderbrand, 2012; Lloyd, 2006)

Decade	**Average annual population**	**Alluvium volume m³**
1851-1860	2795	3,493,000
1861-1870	365	647,000
1871-1880	305	774,000
1881-1890	224	566,000
1891-1900	229	581,000
1901-1918	Pund & Co	440,000
1919-1947	GSG Amalgamated	766,000
total		7,267,000

Table 4: Details of sludge dams on Three Mile Creek, area and volumes rounded to nearest thousand (see Figure 9 for locations)

Number	**Date (approx.)**	**Wall height**	**Wall Length**	**Area m²**	**Volume (approx.) m³**
Dam 1	1880s	5.2 m	326 m	18,000	47,000
Dam 2	1880s	2.9 m	151 m	7000	10,000
Dam 3	1911	2.3 m	248 m	19,000	22,000
Dam 4	1911	3.0 m	316 m	42,000	63,000
Dam 5	1940s	1.0	142 m	14,000	7000
Dam 6	1940s	0.5 m	71 m	26,600	7000
Dam 7	1940s	0.5 m	61 m	19,000	5000
Kassebaum	1881	5.0 m	96 m	7000	18,000
total					179,000